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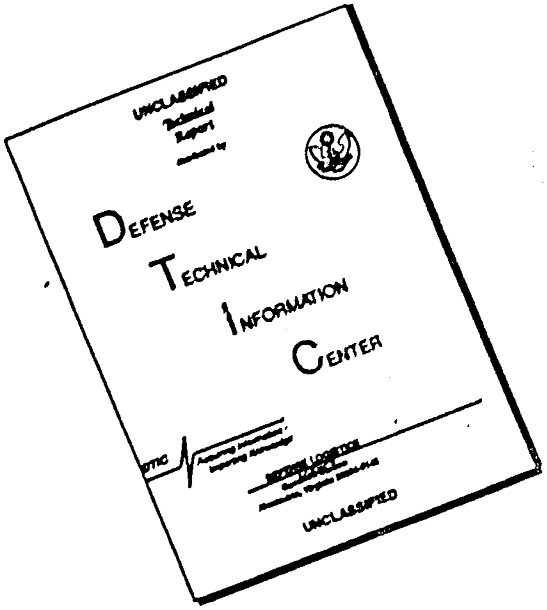

TEXTILE SERIES REPORT

NO. 123

A SURVEY OF 18-OUNCE BLENDED SERGE FABRICS: WEAR RESISTANCE

QUARTERMASTER RESEARCH & ENGINEERING CENTER
CLOTHING & ORGANIC MATERIALS DIVISION

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A SURVEY OF 18-OUNCE BLENDED SERGE FABRICS: WEAR RESISTANCE

Louis I. Weiner

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FOREWORD

During World War II, since some natural textile fibers were in short supply, both the United States and Germany turned their attention to problems related to the serviceability of textile materials. The Germans concentrated on using man-made fibers of less general serviceability than some of the natural fibers and on attaining the highest possible efficiency from their limited industrial capacity. A collection of the more important wartime German publications on the serviceability of textiles was translated after the war and published in a report issued through the U. S. Department of Commerce. In the United States, the pressure on the industrial capacity did not become critical until the latter part of 1944. During this time and in the immediate postwar period, intensive studies on textile serviceability were carried out by Dr. Stanley Backer and the late Mr. Seaman J. Tanenhaus, both of whom were associated with the Quartermaster Development Laboratories.

With the rapid growth of the United States economy and the increased availability of fibers of all types, military programs on serviceability were de-emphasized and effort was concentrated rather on the protective aspects of fabric performance. However, upon the outbreak of war in Korea, wool prices skyrocketed and, simultaneously, wool production in this country declined. As a result, in 1951 the Quartermaster Corps, acting on recommendations from Industry and on the advice of the National Research Council, initiated studies to determine the feasibility of extending the available supply of wool by incorporating significant amounts of man-made fibers into the 18-ounce serge and producing prototype fabrics that could be used in place of the all-wool in the event of further emergency situations. These studies, reported in the QM R&E Textile Series Report 98, "Blends of Wool-Type Fabrics," have provided considerable valuable data for the establishment of criteria for optimum functional performance.

Subsequent research and development efforts in the textile fiber field led to the commercialization of several new man-made fibers and to the modification and improvement of older man-made fibers. These developments stimulated a broad spectrum of studies both within the military departments and outside them. The present report represents one phase of a study conducted jointly by the Quartermaster Corps and the Air Force. It covers field and laboratory evaluation of the wear resistance of 13 experimental serge fabrics containing some of the new man-made fibers. Two earlier phases were concerned with the procedures used in manufacturing these and 8 additional fabrics (Textile Series Report 106) and with their complete analysis in the laboratory (Textile Series Report 107).

This report on wear resistance is timely because wider applications for man-made fiber blends and the development of new theories to explain wear have aroused considerable interest in the United States in wear resistance. Recent publications of the National Cotton Council and the Armour Research Foundation indicate the renewed importance being given to this subject. In addition to providing laboratory and field wear test data, this report includes information about some of the mechanisms that may be applicable to the wear of textile fabrics. It is hoped that this information will prove useful and that it will stimulate additional studies on the subject.

A great many individuals contributed to this three-phase study. Mr. Constantin J. Monego, formerly Project Engineer in charge of the wool conservation program at the Quartermaster Research and Engineering Command, was the author of the first phase report. He also supervised the contract work at the Harris Research Laboratories that resulted in the second phase report by Dr. John Menkart. In this, the third phase, wear tests were carried out at the Quartermaster Field Evaluation Agency under the supervision of Mr. Johnnie M. Matthews and Mr. Paul James; abrasion tests at the Quartermaster Research and Engineering Command were carried out under the supervision of Mr. Harry F. Smith and Mr. Clarence J. Pope. Special acknowledgement is given to Mr. Harry F. Smith, who developed the sand abrader and directed its use, and to Miss Editha Stone, who edited this report.

S. J. KENNEDY
Director
Clothing and Organic Materials Division

Approved:

DALE H. SIELING, Ph.D.
Scientific Director

MERRILL L. TRIBE
Brigadier General, USA
Commanding

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ABSTRACT

The wear resistance of 13 experimental blended serge fabrics was evaluated on the Wool Fabric Course of the Quartermaster Field Evaluation Agency at Fort Lee, Virginia, and, by means of the Stoll Flex Abrader and a new Sand Abrader, at the Quartermaster Research and Engineering Laboratory in Natick, Massachusetts.

The evaluation indicates that wear resistance is influenced by blend composition and the energy-absorbing ability of the component fibers. The results of the sand abrasion tests were found to be similar to those produced on the wool course and suggest that the sand abrader may be useful in indicating wool course results. The theory behind some of the mechanisms that may influence the wear of textile fabrics is included in order to point out additional approaches to the problem of wear.

A SURVEY OF 18-OUNCE BLENDED SERGE FABRICS: WEAR RESISTANCE

1. Introduction

This is the third in a series of reports summarizing the results of a study of alternates for the 18-ounce all-wool worsted serge* used by the military forces of the United States. The purpose of the study was to develop fabrics that would meet or exceed the performance standards established for the all-wool serge and that would contain a significant proportion of fibers that, in the event of an emergency situation, would be more readily available than the grades of wool required to produce the standard serge.

The first report (1) described the manufacturing procedures used in the production of 20 experimental blends and the physical properties of the finished fabrics and of some fabrics selected from intermediate stages of production. The second report (2) presented a laboratory evaluation of the fabrics. The present report, the third in the series, is concerned with a comparison of the wear resistance of the fabrics as determined on the Wool Fabric Course of the Quartermaster Field Evaluation Agency at Fort Lee, Va., and in the Quartermaster Research and Engineering Laboratory in Natick, Mass. It is possible that the results of troop acceptability trials conducted by the Air Force on garments made from a number of the experimental fabrics may be published as a fourth and final report in this series.

The need for research on blended serge fabrics was recognized during the Korean War when the gap between the production and consumption of wool, plus unsettled market conditions, led to a critical domestic supply situation. Data for annual wool production and consumption computed (1) from statistics of the National Association of Wool Manufacturers for the period 1940 to 1954 are given in Table I.

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* Described in Specification MIL-C-823B as Type I, Class 1.

TABLE I

Annual U.S. Production and Mill Consumption of Wool*
(millions of pounds)

Year	Production	Consumption
1940	188	408
1942	202	604
1944	188	623
1946	170	748
1948	137	693
1950	119	635
1952	127	466
1954	135	383

---

* Scoured basis.

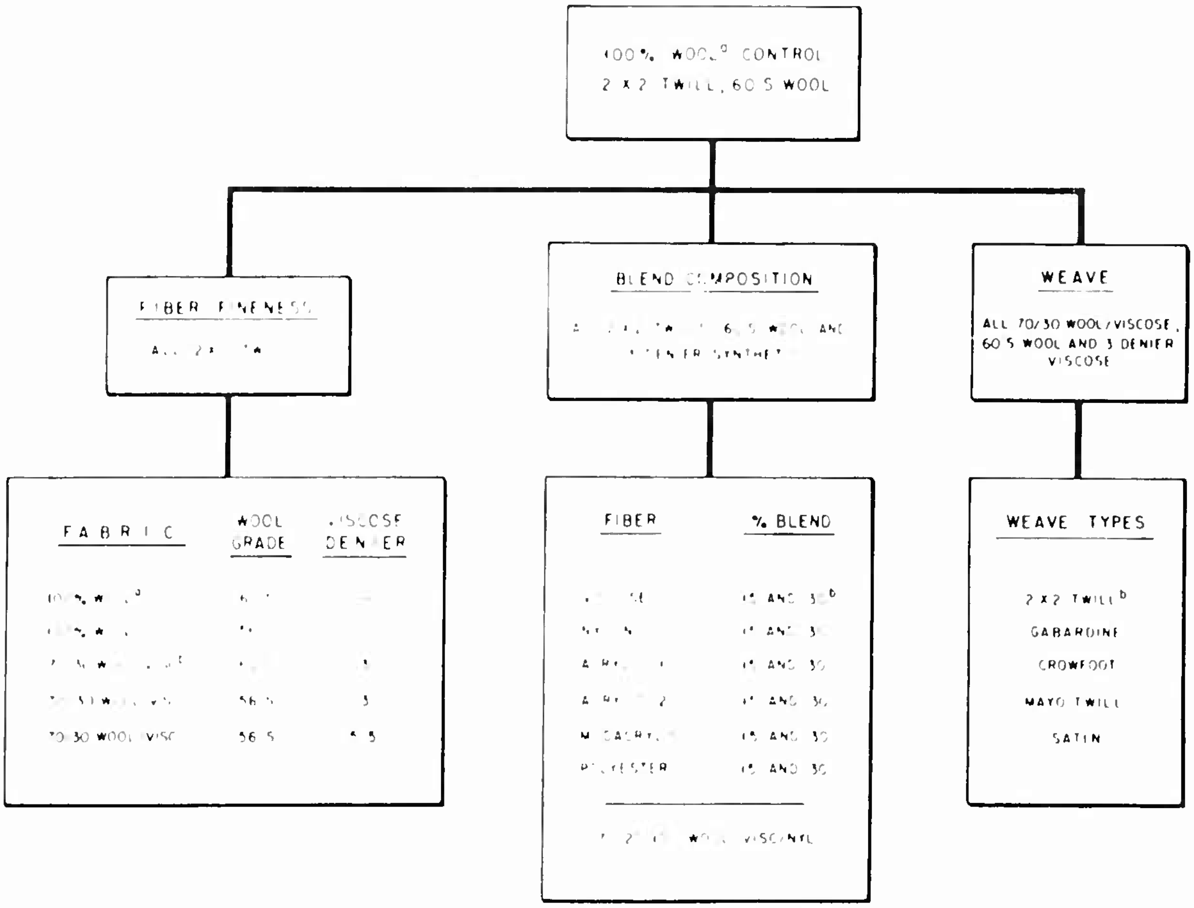
In 1950, production dropped to 119 million pounds, the lowest amount for the entire 14-year period. As an immediate emergency step, specifications were developed for a wool/nylon and a wool/viscose 18-ounce serge. Neither fabric proved to be completely satisfactory. The former presented problems in sewing and tailoring and the latter lacked durability.

In 1953, the Quartermaster Corps initiated a joint program that was supported in part by the Air Force. This program led to the production of 20 experimental fabrics that varied in fiber fineness, blend composition, and weave. Among the fabrics varying in fiber fineness were three that used the coarse 56's grade of wool. It was hoped to establish whether or not the more readily available 56's would be as satisfactory as the standard 60's wool from the standpoint of acceptability. Also, it was anticipated that the 56's wool would have a longer wear life than the 60's; thus it was used both in a 100 percent wool construction and in blends with viscose. In the blend composition series the thermoplastic synthetic fibers were limited to 30 percent, since a higher ratio might have impaired the ability of the fabric to offer protection against some types of thermal weapons. In the weave series it was hoped that weaves with longer floats, such as the Mayo twill and satin, would increase the wear life of the fabric and thus permit larger percentages of viscose.

Table II lists the experimental fabrics grouped according to variables in composition and construction.

TABLE II

Experimental Fabrics Grouped According to Variables in Composition and Construction



Complete laboratory data on the physical properties of these fabrics (2) are tabulated in Appendix A of this report. Recommendations based upon the laboratory data are quoted below (from Reference 2, pp. 37-39)* as background information for the wear resistance findings which follow.

---

* Trade names of the synthetic fibers are omitted from the quotation and generic names are used instead, inserted within brackets.

"Weave

"The Mayo twill and the satin fabrics are appreciably different in hand and appearance from the standard 2/2 twill. They are appreciably limper and less wind resistant than the standard, and, used warp-flush, are predicted to have a low resistance to wear. They may be excluded from further consideration. The crowfoot differs little from the twill in either appearance or measurable properties; no advantage from its use is readily apparent. The garbardine is similar to the twill in its appearance and durability characteristics, but appears to offer some advantage in wearer comfort by virtue of its greater softness and lower bending stiffness; it is recommended for further study in compositions other than the 70/30 wool/viscose blend here evaluated.

"Wool Grade

"The 18-ounce serge made from 56's wool differs little from that composed of the standard 60's in functional properties, but has a slightly harsher hand. It seems likely that an appreciable dilution of the 60's by the coarser wool can be accomplished before even the effect on hand becomes apparent to anyone except an expert. The use of 56's wool, as a substituent or diluent, for broadening the base of the wool supply appears a useful approach.

"Viscose Rayon

"The introduction of viscose rayon causes lowering in the resistance to wetting, and a greater ease of ignition on exposure of the fabric to flame. With 30% viscose (but not 15%) the fabric is also somewhat leaner and harsher than the standard. It is considered that 15% of viscose may be incorporated in the fabric with only a slight loss in functional properties; at the 30% level, this loss is becoming noticeable. There is little to be gained from increasing the denier of viscose from 3 to 5-1/2 in blending with 56's wool.

"The utilization of viscose (20%) in a ternary blend with wool (70%) and nylon (10%) appears to have merit. The fabric has the ready liquid moisture adsorption characteristic of the viscose blends, but in terms of other comfort and appearance factors, and in durability, it behaves like an all-wool or wool-nylon structure. This composition, offering as it does an appreciable reduction in wool requirements and a lowering in materials costs with substantial maintenance of functional properties, merits serious consideration as a potential alternate for the all-wool serge. A sewing finish is needed for its manufacture into garments on a production scale.

"Nylon and [Polyester]

"The incorporation of these two fibers, at the levels evaluated, causes no significant change in the comfort or appearance rating of the fabric, and results in an appreciable increase in durability. On the other hand, thermal protection is diminished, all the fabrics exhibiting

melt-dripping once ignited. The lowering in thermal resistance is least evident in the 15% nylon blend, and this construction therefore appears the most promising of those in this group as a potential alternate for the all-wool 18-ounce serge. The application of an effective sewing finish would be needed for its utilization.

"As noted above, the blend containing 20% viscose and 10% nylon approaches the 15% nylon blend in its functional properties, with one exception, its greater ease of wetting. Since the properties of the two structures are so nearly similar, the ternary blend, which is more economical in wool usage, is to be preferred.

"The Acrylics /and Modacrylic/

"In the structures under consideration, the incorporation of the acrylic /and modacrylic/ fibers leads to an increase in bending stiffness of the fabric on exposure to the type of pressing operation usual in wool garment manufacture and in dry cleaning. The effect is largest in the case of the /modacrylic/ (where it is accompanied by surface glazing), intermediate in /acrylic-2/ and least in /acrylic-1/. This point apart, the fabrics are broadly equivalent to the all-wool standard in their comfort, appearance, and durability characteristics. They do not equal the all-wool standard in their thermal protection performance, especially at the 30% level. For applications where protection from fire is an important criterion of suitability, these blends are somewhat less desirable than the all-wool standard.

"On the basis of tendency to stiffen and glaze in pressing, the relative order of desirability is: /acrylic-1/, /acrylic-2/, and /modacrylic/.

"Like the nylon and /polyester/ structures, those containing the acrylics /or modacrylic/ require the use of a sewing finish for satisfactory garment manufacture*.

"Overall Order of Desirability of Experimental Fabrics

"1. Fabrics recommended for field use:

a. 70/20/10 wool/viscose/nylon
b. 85/15 wool/nylon
c. 70/30 wool/viscose

"2. Fabrics recommended for other uses. There are forms of wear in which thermal protection is a minor factor in the overall merit rating;

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*Frederick, E. B. et al. Analysis of Sewing Characteristics of Various Experimental 18-oz. Serge Fabrics, TEL Rpt. 191, QM R&E Command, Natick, Mass. (1958)

examples are service clothing, and such combat garments as are worn under an outer layer of thermally resistant clothing. For such applications the following materials, in addition to those listed above, are considered suitable, in the order given:

d. 70/30 wool/nylon
e. 70/30 wool/ [polyester]
f. 70/30 wool/ [acrylic-1]
g. 70/30 wool/ [acrylic-2]." (end of quote)

The conclusions reached as a result of these former laboratory studies must be tempered by the realization that each of the materials analyzed represented a sample obtained from *one* production lot produced by *one* manufacturer. It would be expecting too much to assume that the properties observed would represent an average performance for *all* blends similar in fiber content and weave. It is conceivable that alterations in blending or manufacturing techniques might lead to marked changes in one or more of the fabric properties. In most cases, however, the general trends in performance which were observed have a valid theoretical foundation that may be used as a basis for planning more production studies.

2. Mechanisms of Wear

Evaluation of the abrasion and wear resistance of textile fabrics continues to be an extremely difficult problem. The difficulty arises in part from the lack of a significant body of data relating the laboratory and accelerated field wear of a variety of fabric types to their performance in actual use. In addition, the multiplicity of laboratory abrasion instruments and the great variety of conditions under which they may be used create problems in selection which cannot be readily resolved on the basis of existing knowledge about the significance of the abrading mechanisms. Finally, it is becoming increasingly recognized that the response of some fabrics to specific types of abrasion is often caused by subtle interactions between the fabric and the abradant which do not always reflect the actual mechanical properties or wearability of the fabrics. For example, it has been shown (3) that minute amounts of a normal fabric finish can lead to a rather large increase in laboratory flex abrasion resistance, although the same finish may not contribute to additional wear in the field. On the other hand, it is probable that in laboratory abrasion testing, an equilibrium situation occurs in which rather high temperatures are reached and sustained during the course of the test. These temperatures may be sufficiently high to cause a change in the stress-strain properties of some thermoplastic fibers and thus lead to their more rapid failure and a decrease of their abrasion resistance.

Another problem is that the determination of a valid abrasion end point is more difficult for wool blends than for unblended fabrics. During the abrasion of blends of wool with high-tenacity nylon, the wool is selectively removed from the fabric by the

rubbing and snagging action of the abradant. Often a major portion of the wool fibers is rubbed from the fabric, leaving only a skeletal framework of nylon. Obviously such a fabric is no longer useful for its original purpose, although it still would have considerable residual abrasion resistance if the abrading action were continued to rupture. In the second report (2) of this series, the laboratory evaluation of abrasion resistance was based upon an end point determined by the denuding of wool from the fabric structure. While this end point is logical from the point of view of the appearance of dress or semi-dress clothing, it would not be as logical from the point of view of combat clothing applications. Observations during combat indicate that while small holes are enlarged by continued abrasion until ultimate failure of the item occurs, a combat garment is seldom discarded because of surface abrasion of the fabric.

If a textile structure is considered to be relatively isotropic, some of the theories and mechanisms which have been derived for the wear of metals and other homogeneous solids may be visualized as applicable to textiles also. But rather than describe these mechanisms as such, it may be preferable to consider the following factors that have been observed to influence fabric wear: frictional lubrication, frictional heat, mechanical wear, adhesive and abrasive wear, cutting, snagging, and structural influences, and to discuss their implications with regard to textile problems. It is not possible to define each of these factors in unqualified terms or to assess its overall importance for any given wear system. One or more of the factors may predominate, depending upon the material being tested and the nature of the test. However, it will be of interest to briefly review the possible significance of each factor on some types of observed wear.

a. Frictional Lubrication

The term "frictional lubrication" is used to characterize the action of abradant systems in which friction predominates and can be controlled by the use of a lubricant. Lubrication may be either hydrodynamic or boundary.

In hydrodynamic lubrication, the load on the lubricated member is not great, there is a thick lubricant film, and the relative speed between the surfaces is sufficiently high to produce a separating pressure. This type of lubrication prevails in a journal bearing, where the coefficient of friction is related primarily to the viscosity of the lubricant, the speed of rotation of the bearing, and the load. It is doubtful that hydrodynamic lubrication is signficant in the wear of conventional textile fabrics.

In boundary lubrication, on the other hand, the load on the lubricated member is greater and the film thickness is less. In abrading a fabric against a metal blade, as in the Stoll flex test (4), we find this type of lubrication. During the sliding action, some of the asperities of the metal are able to penetrate the thin

lubricant film and shear the fiber substance. Since part of the total area of asperities is supported by the film, only that area that actually penetrates it will participate in the shearing action. Thus in boundary lubrication the average size, but not the number, of particles sheared is reduced.

The mechanisms involved in wear reduction as a result of frictional lubrication are similar to those described below for adhesive wear. However, the effect is often so very specific that it is of interest to discuss it separately. For example, Figure 1 shows a marked reduction in the Stoll flex abrasion resistance of a Quarpel-treated sateen with successive cycles of extraction. The high initial abrasion resistance of the Quarpel-treated fabric as compared with that of the untreated control is due to the high degree of boundary lubrication between the metal blade of the tester and the treated fabric, with the result that the average size of abraded particles is reduced to a point where the time to rupture increases markedly. This difference between lubricated (treated) and unlubricated (untreated or extracted) samples did not appear to be as great in the sand abrader or on the FEA wear course.

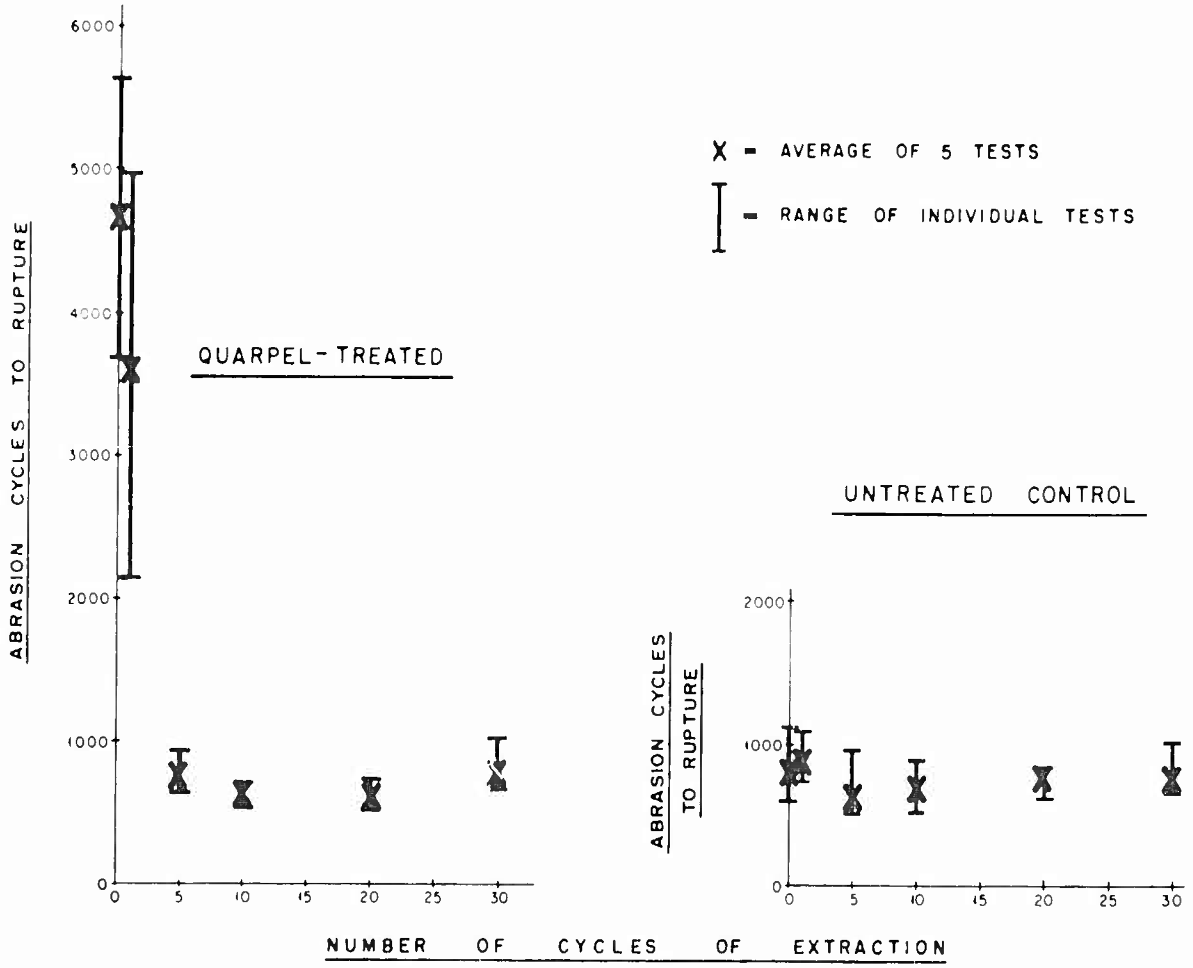


Figure 1. Variation in Flex-Abrasion Resistance With Cycles of Chloroform Extraction

b. Frictional Heat

Work expended in overcoming friction is liberated as heat. Since the actual area of contact between surfaces is minute, the heat generated may be very great. The temperature rises approximately 50 degrees (C) for Wood's alloy, 300 degrees (C) for lead, and 450 degrees (C) for constantan, when small cylinders of these materials slide against a steel surface at 500 cm/sec under a load of 100 grams (5). With some materials, the temperature drops off rapidly at slower sliding speeds.

Since non-metals are poor conductors, high frictional heat surface temperatures may be reached more readily with them than with metals. It would be of interest to measure the temperatures reached at the surface of a fabric during a wear test. In one limited experiment (6), a 10 degree (C) temperature rise was observed in the center of the flex blade of the Stoll machine at a point .025 from the rubbing edge. The temperature at the edge of the blade would have been much higher, the temperatures reached by the asperities themselves would have been extremely high although in metal-to-metal sliding it has been observed that the surface temperature does not exceed the melting point of the metal.

In fabric abrasion, it is conceivable that local temperatures from frictional heat could be sufficiently high to alter the stress-strain behavior of the components and thus result in the premature failure of low-melting-point fibers. It is probable that the rather poor agreement observed in this study between the laboratory abrasion data and wear course data for the modacrylic blends, as will be noted in a later section, was due to the higher temperatures reached in the laboratory and the consequent more rapid loss in mechanical properties.

c. Mechanical Wear

The fact that fibrous materials with high energy-absorbing capacities show higher levels of wear, regardless of the type of wear test to which they are subjected, demonstrates that two significant elements in wear performance must be the repeated application of stress (tensile, shear, compressive, or torsional), and the ability of the fiber to resist deformation until final rupture occurs.

A number of studies have been made to relate work-to-rupture and abrasion resistance (7-9). The most precise approach is that of Hamburger (7). In his study, durability coefficients were computed from the slope of the lines to the mean ordinates of strength loss versus cycles plots for the abrasion of yarns rubbed, serigraph fashion, on a Taber abrader. In a corresponding manner, energy coefficients were computed from the slopes of the lines to the mean ordinates of the percent of ultimate strength versus the percent of elongation of the stress-strain curves of the yarn specimens after mechanical conditioning. The relationship between these two coefficients was quite linear and was subsequently verified by studies of additional yarn types.

In tests conducted (10) on nylon/cotton blended yarns, work-to-rupture was computed from the areas under the stress-strain curves of non-mechanically conditioned yarns, and cycles-to-rupture were obtained from the Walker-Olmstead (11) yarn abrader. These data (Figure 2) show a fairly linear correlation between abrasion cycles (A) and the square of work-to-rupture (W^2), but the relationship departs from linearity for the non-square data, primarily because of the exceptionally high abrasion resistance of one sample, which was a 100 percent spun nylon yarn. Probably the presence of as little as 20 percent of cotton in a blended structure of this type brings into play mechanisms other than those related to the mechanical properties of the yarn itself.

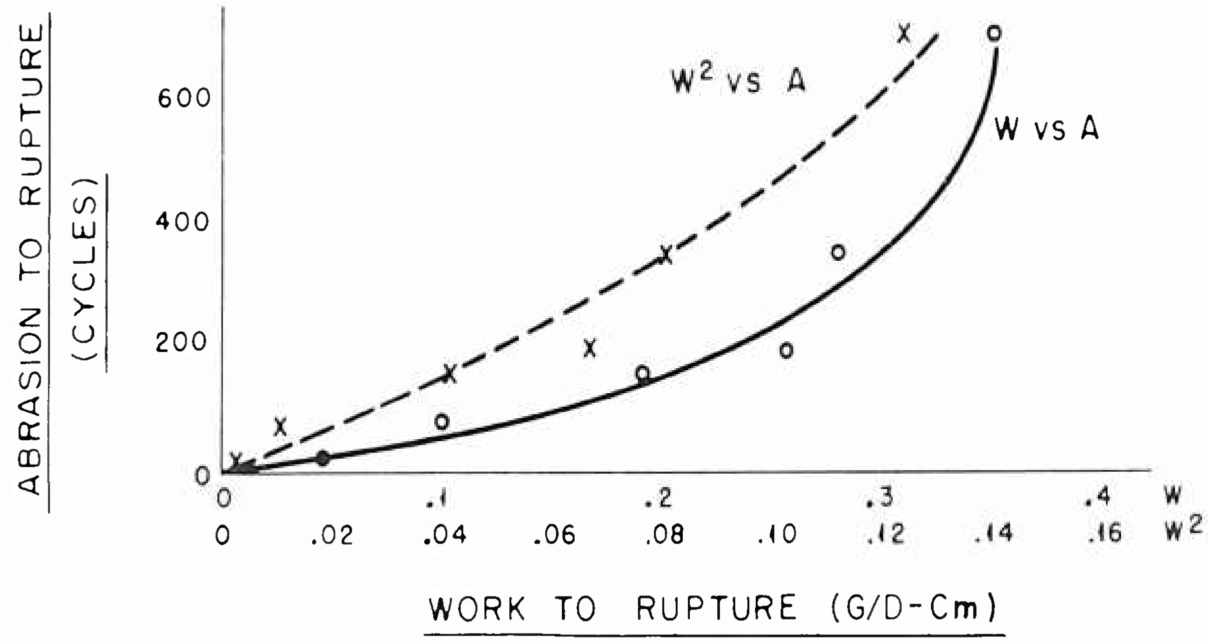


Figure 2. Relationship of Abrasion and Work-to-Rupture of Nylon/Cotton Blended Yarns

d. Adhesive and Abrasive Wear

The complex interactions that take place during fibrous wear make it extremely difficult to clearly segregate the specific effects due to the various mechanisms which have been advanced. Probably frictional parameters can be grouped under the term "adhesive" wear and the other mechanical effects, including cutting, under "abrasive" wear, leaving snagging as a final mechanical factor related more to the specific geometry of the gross fabric structure than to the finer interactions that comprise adhesive and abrasive wear.

1) Adhesive Wear. Archard bases his concept of adhesive wear (12) on a sliding process in which circular junctions exist momentarily.

between the abradant and the material being abraded (see Fig. 3). These junctions may or may not give rise to an abraded particle, which he assumes would be hemispherical and would adhere to the harder surface. Archard treats the possibility of the junction giving rise to an abraded particle on a probability basis, as follows:

> If each circular junction has an area equal to $\pi d^2/4$, and the total area of contact is **A**, then the number of junctions must equal the ratio of **A** to $\pi d^2/4$. From friction theory, the real area of contact is the ratio between the load (L) and the penetration hardness (p) of the softer material, thus:
>
> $$N = \frac{A}{\frac{\pi d^2}{4}} \qquad N = \frac{\frac{L}{p}}{\frac{\pi d^2}{4}} \qquad N = \frac{4L}{\pi d^2 p} \tag{1}$$
>
> If we assume that each junction lasts for a distance (d) equivalent to the diameter of the junction, then for a sliding distance of $\Delta \ell$ we have a total of N_t junctions:
>
> $$N_t = N \frac{\Delta \ell}{d} = \frac{4 L \Delta \ell}{\pi d^3 p} \tag{2}$$
>
> If we assume that each junction has a probability (K) of forming an abraded particle, then the total number of such particles is:
>
> $$N_p = K N_t = \frac{4 K L \Delta \ell}{\pi d^3 p} \tag{3}$$
>
> Since we assume that each particle is hemispherical in shape and has a volume equivalent to $\frac{\pi d^3}{12}$, then the volume of wear (ΔV) is:
>
> $$\Delta V = N_p \frac{\pi d^3}{12} = \frac{4 K L \Delta \ell \pi d^3}{12 \pi d^3 p} = \frac{K L \Delta \ell}{3p} \tag{4}$$
>
> or the volume of wear per unit length is:
>
> $$\frac{\Delta V}{\Delta \ell} = \frac{K L}{3p}$$

Thus the rate of wear ($\Delta V/\Delta \ell$) is directly proportional to the load and inversely proportional to the hardness of the softer material. "K" is a

constant of proportionality which represents the probability of forming an abraded particle.

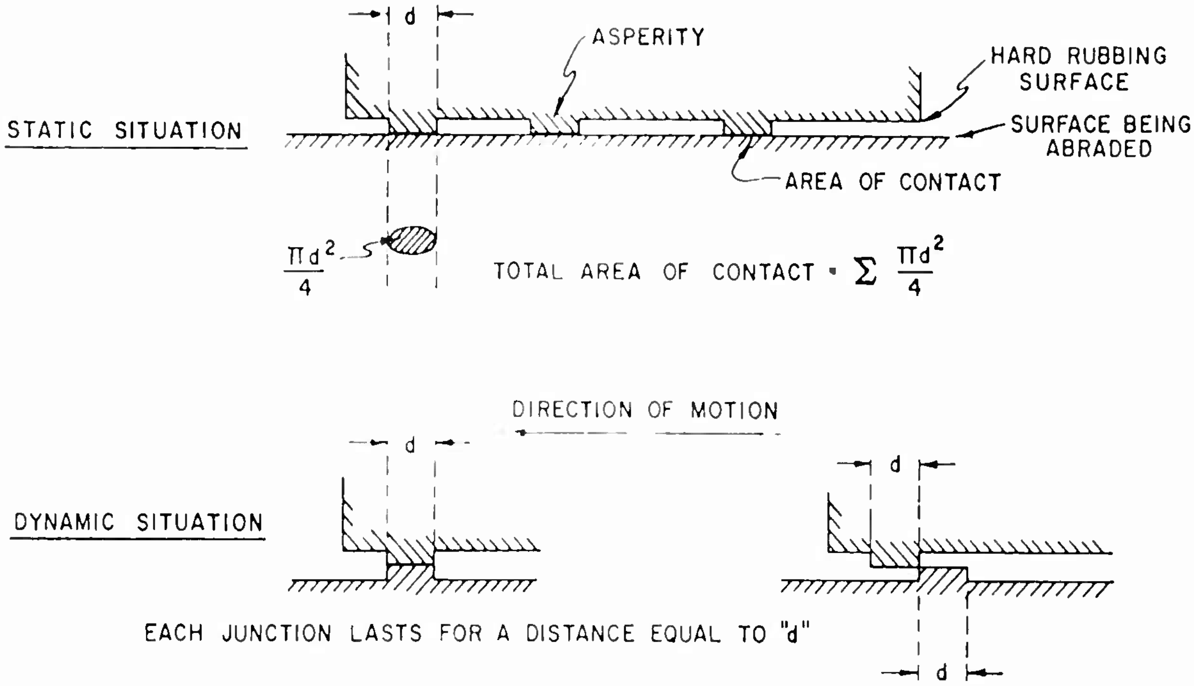
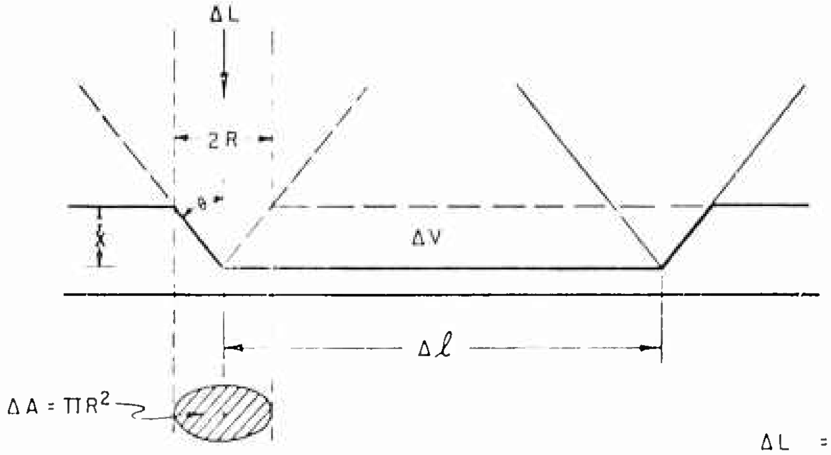


Figure 3 Concept of "Adhesive" Wear

Archard's theory is partially consistent with observations made during the abrasion of textile structures. With respect to equation (4), considerable data have been obtained showing that the rate of wear increases with the load (13), in fact this is almost self-evident in most wear situations. On the other hand, it is not easy to visualize what could constitute a measure of the second factor, penetration hardness, since textiles are not homogeneous structures and the anisotropic structure of individual fibers precludes the use of a single value for this parameter that would be meaningful in terms of this adhesive wear theory. There is little in the way of available data that might provide a clue as to the penetration hardness of textile fibers. Backer (14) studied the compressional properties of several textile fibers in which the stress was applied laterally (perpendicular to the longitudinal axis of the fiber), and measured the major and minor axes of the ellipse of deformation at the intersection of the fiber with the compressing surface. He also studied the compressional properties of small cylinders cut from the fibers in which the stress was applied parallel to the longitudinal axes. If his data are accepted as a rough indication of penetration hardness, it would be possible to make a rough association between this measure and the rated abrasion resistance for selected fiber types. In applying Archard's probability factor (K) to textiles, the influence of lubricants would be included. In a well-lubricated

textile, the K factor would be low and the wear rate would be correspondingly low. The constant 3 is a shape factor which varies with the assumed or measured geometry of the abraded particles. In general, therefore, Archard's theory of adhesive wear provides a useful means of approaching a study of the wear resistance of textiles and should form the basis for more detailed investigations of wear mechanisms in heterogeneous materials of this type.

2) Abrasive Wear. Rabinowicz considers abrasive wear (15) as a process whereby a hard, rough surface "ploughs" grooves in a softer material. Material from the grooves is abraded in loose form. This is considered to be 2-body wear. When hard particles, such as sand, are trapped between two sliding surfaces, 3-body wear occurs. Rabinowicz developed a concept (see Fig. 4) in which a cone of hard material is assumed to be pressed into a softer material and to be moved a short distance. The volume of material that is ploughed or cut out per unit length increases directly with the load and is inversely proportional to the hardness of the material being ploughed. The equation for this action is similar to the one developed by Archard for adhesive wear and further demonstrates the interrelatedness and complexity of wear phenomena.



L E G E N D

ΔL = LOAD CARRIED BY FILAMENT
p = HARDNESS OF MATERIAL BEING ABRADED
ΔV = VOLUME OF ABRADED MATERIAL
$\Delta \ell$ = LENGTH OF ABRADED PATH
R, θ = CONE PARAMETERS

FROM FRICTION THEORY $p = \frac{\Delta L}{\Delta A}$

$$\Delta L = p\Delta A = p\pi R^2$$

$$\Delta V = RX\Delta \ell = R^2 \cot\theta \Delta \ell$$

$$\frac{\Delta V}{\Delta \ell} = R^2 \cot\theta = \frac{\Delta L \cot\theta}{\pi p}$$

Figure 4. Concept of "Abrasive" Wear

e. Cutting

It is difficult to determine whether true cutting, as it occurs in metal working, is significant in the wear of textiles. It is probable

that the idea of cutting is embodied in the ploughing concept of abrasive wear, as advanced by Rabinowicz, in which a softer material is deformed by a harder in proportion to the load. Analogously, a cutting tool must be harder than the material being cut and the greater the load the more rapidly will the cutting take place. In metal cutting, two fundamental processes are involved: a compression, with resultant flow up the face of the cutting tool; and either a rupture or plastic flow in a direction generally perpendicular to the tool (16). When rupture occurs, as with brittle materials, a discontinuous chip results; when plastic flow occurs, as with ductile materials, a continuous chip results.

f. Snagging

Wear failure may also occur as a result of gross mechanical interactions between the abradant particles and the components of the fabric system which may be described under the general category of snagging. Snagging implies that an instrument external to the fabric is partially inserted into the fabric structure and, by relative motion with respect to the fabric, applies a force that results in the removal of an element of structure or in the development of a strain that may lead to rupture. The final outcome of snagging depends not only on the geometry of the fabric but also on the geometry and mechanical properties of the snagging element, its speed of motion, its orientation with respect to the components of the fabric structure, and the depth of its penetration into the fabric. Studies made of gross snagging mechanisms not associated with wear as such (17) reveal that the height and amplitude of a yarn float is related to ease of snagging and that filament yarns, because of their lower twist, are more susceptible to snagging than spun yarns.

g. Structural Influences

Much of the literature on the abrasion and wear resistance of textiles is concerned with the effect of such structural factors as yarn count, yarn twist, yarn and fiber crimp, and fabric texture and weave, and with the effect of finishing, particularly with resins. In fact, most of the effort of the military to improve the wear of combat items has been concerned with these and particularly with the geometric factors.

The fact that the fabrics are not isotropic and that their structure varies along their length and width as well as between their face and back suggests that this non-homogeneity may be of significance. The effect of weave, for instance, has been studied by Kaswell (18) and Backer (19), both of whom found that the direction of rubbing, the side of the fabric (face or back) exposed to the abradant, and the location of the stress-bearing yarns have a marked influence on abrasion resistance. In a recent study (20) of the sateen weave, it was found that there is an almost constant amount of difference between warp and filling direction abrasion resistance on the back of the fabric, and

between filling and warp direction abrasion on the face of the fabric. This is shown in Table III.

TABLE III

Number of Abrasion Cycles to Rupture of Four Different Sateens, Abraded on Face and Back in Warp and Filling Directions

	Warp Direction	Filling Direction	Difference
Sample 1			
Back	890	630	260
Face	530	810	280
Sample 2			
Back	1530	930	600
Face	1000	1610	610
Sample 3			
Back	2160	1200	960
Face	1480	2200	720
Sample 4			
Back	970	670	300
Face	660	910	250

These data demonstrate one of the unique features of a satin weave: that its response to abrasion is similar to what one might expect, at least theoretically, from a double-woven fabric with one layer composed of filling yarns and the other layer composed of warp yarns. Assuming that the 2-layer fabric is abraded on the filling-yarn surface and in a direction perpendicular to the filling yarns, the warp yarns, which in this instance would constitute the stress-bearing system, would remain practically unaffected by the action of the abradant until the filling yarns are very nearly worn through. Additional abrasion would then be required to sever the stress-bearing warp yarns. If the direction of abrasion is changed by 90° so that it is perpendicular to the warp yarns, the filling yarns become the stress-bearing system and after they are worn through, the warp yarns contribute no additional abrasion resistance. Accordingly, as shown in Table III for abrasion on the back of a sateen (corresponding to the filling flush side of the theoretical fabric), warp direction abrasion resistance is always higher than that of the filling. On the other hand, in the case of abrasion on the face of a sateen, it is the filling direction abrasion resistance that is always higher than that of the warp. The constant difference between the filling and the warp for face and back abrasion demonstrates the independence in response of orthogonal yarn systems.

These geometric factors are worthy of continued study. However, one must still take into account the other mechanisms of wear we have referred to.

3. Field Wear and Laboratory Test Results

a. Field Wear Tests

Test phases and fabrics. For the wear resistance comparisons of this study, accelerated wear trials of the experimental blended serge fabrics were conducted, in two phases, on the Wool Fabric Course at the Quartermaster Field Evaluation Agency, Fort Lee, Virginia. The first phase was conducted from 26 August to 31 October 1957 and involved the comparison of six fabrics, including an all-wool control from the original group of 21 (see Table II), plus a new control--an 18-ounce all-wool serge in the OD shade 33. The second phase was conducted from 10 June to 29 July 1960 and included seven other fabrics from the original group plus the same OD 33 control just mentioned. Thus only 13 of the 21 serges of this study (12 blends and the original all-wool control) were evaluated on the wear course. They are listed according to phase in Table IV. Not evaluated at this time were the 85/15 wool/nylon, the 70/30 wool/viscose in gabardine, crowfoot, and Mayo twill weaves, and the 70/30 and 85/15 wool/acrylic-1 and wool/acrylic-2 blends. Both tests are described in detail in reports T-53 and T-170, "An Accelerated Wear Test of Wool and Synthetic Fiber Blended Serge Fabric" by the Quartermaster Field Evaluation Agency, Fort Lee, Virginia, from which the following data have been taken.

TABLE IV

Fabrics Evaluated on the Wear Course During the Phase I and Phase II Tests

	Code*	Description
Phase I	A_1	100% wool control (OD 33)
	B_1	100% 60's wool (original control) twill
	C_1	100% 56's wool twill
	D_1	70/30 60's wool/3-den viscose twill
	E_1	70/30 60's wool/3-den viscose satin
	F_1	70/30 60's wool/3-den polyester twill
	G_1	85/15 60's wool/3-den polyester twill
Phase II	S_2	100% wool control (OD 33)
	A_2	70/30 60's wool/3-den viscose twill
	B_2	85/15 60's wool/3-den viscose twill
	C_2	70/30 56's wool/3-den viscose twill
	D_2	70/30 56's wool/5.5-den viscose twill
	E_2	70/30 60's wool/3-den modacrylic twill
	F_2	85/15 60's wool/3-den modacrylic twill
	G_2	70/20/10 60's wool/3-den viscose/3-den nylon twill

---

*Letters identify the fabrics, subscripts designate the test phase

The selection of fabrics for the field wear trials was based on their earlier laboratory analysis (2). The twill and satin weaves were selected as representing possible extremes in wear resistance, since prior experience with other combat fabrics had demonstrated the superiority in wear of a satin weave. The two modacrylic fabrics were selected as representatives of the group of acrylic blends. Other comparisons were made between all-wools of different wool grade; wool/viscose blends varying in wool grade, viscose denier, and ratio of viscose to wool; wool/polyester blends varying in ratio of polyester to wool; and two nylon/wool blends, one with part of the nylon replaced by viscose. These fabrics were made up into the wear-course style trousers.

Test procedures. The wear course at Fort Lee consists of 30 obstacles arranged along an irregular track approximately one-fourth of a mile long. The obstacles are such as to simulate practically every physical situation in which a combat soldier might be compelled to operate. Personnel running the course climb a stone embankment, crawl across a section of railroad track, slide down a steep cobblestone incline, and crawl along a single-log bridge, through concrete culverts, and across cinders, sand, gravel, and boulders. The number and choice of obstacles to be traversed may be altered for evaluating different types of fabrics. For wool garments, they usually use a group of obstacles collectively designated as the wool-fabric course, which consists of 23 of the 30 obstacles sketched in Figure 5.

Before the test, a group of 60 test subjects wearing standard trousers traversed the wool-fabric course 28 times. The 40 test subjects with the most uniform wear scores were chosen to test the experimental fabrics. They were divided into groups corresponding to the number of fabrics to be tested: 7 for Phase I and 8 for Phase II. Each test subject was issued one pair of each of the experimental trousers. For any given traversal of the course, all of the men in a group wore the same type of trousers but each group tested a different type. Two traversals of the course were designated as one cycle of wear. After each cycle of wear the trousers were dry-cleaned in a mobile unit, using standard dry cleaning procedures. The test continued until each of the experimental trousers had been worn by each group on two traversals of the course.

After dry cleaning, each garment was inspected and scored by skilled observers according to a scoring system which has been used at the Field Evaluation Agency since the inception of accelerated field-wear testing. The scores assigned to various types and degrees of failure are given in Table V. The higher the wear score, the more extensive the damage and the poorer the performance of the fabric.

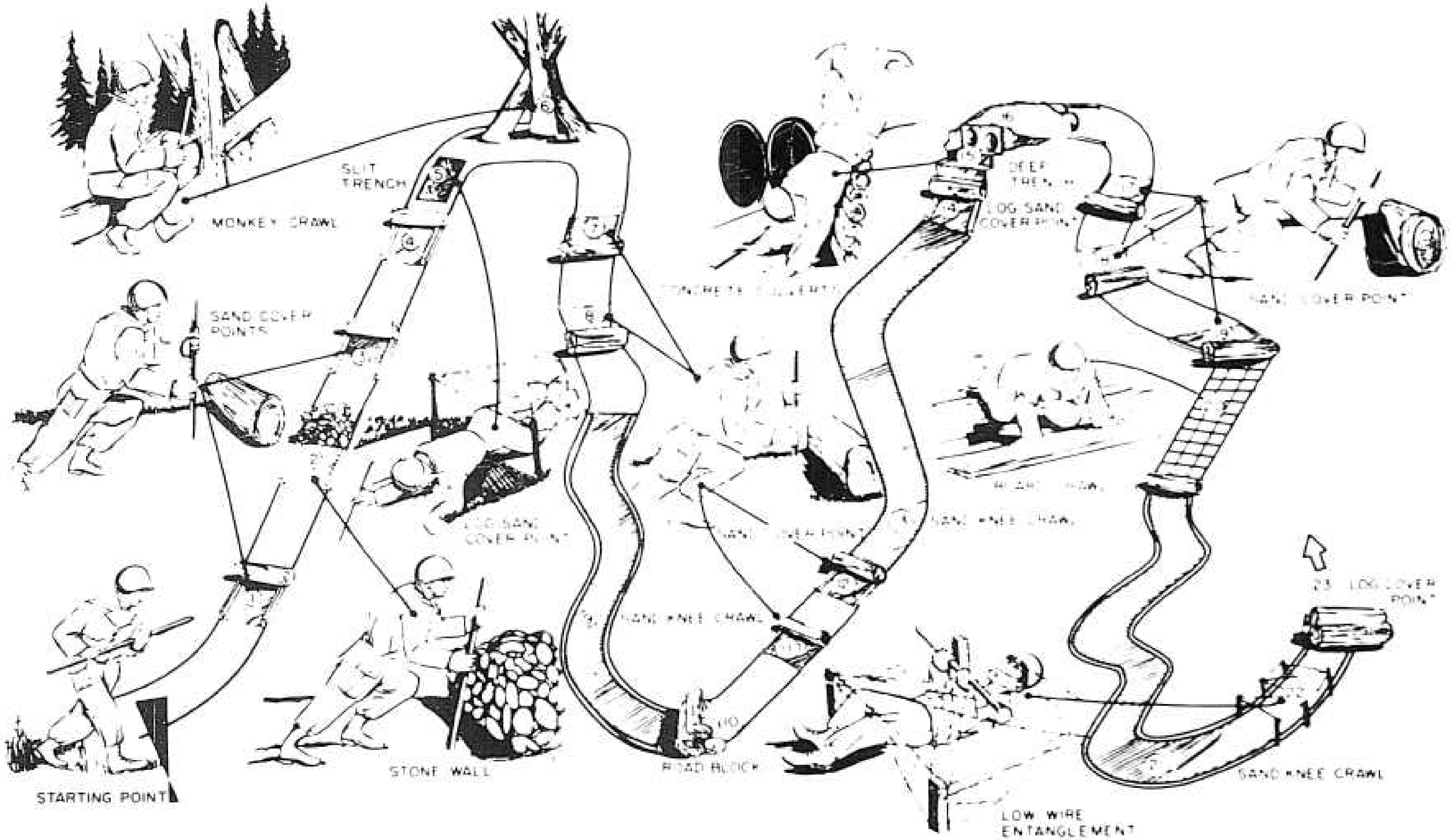


Figure 5. Wear Course at Fort Lee, Virginia

TABLE V

Scoring System Used in Wear-Course Testing

Type of Failure	Degree 1	2	3	4	5	6
	Definition of Degree					
Holes (diameter inches)	<0·25	>0·25 ≤0·5	>0·5 ≤1·0	>1·0 ≤1·5	>1·5 ≤2·0	>2·0
Tears in wear area* (length inches)	<1·0	>1·0 ≤2·0	>2·0 ≤3·0	>3·0 ≤5·0	>5·0 ≤7·0	>7·0
Frays (length-inches)	<1·0	>1·0 ≤3·0	>3·0 ≤6·0	>6·0 ≤10·0	>10·0 ≤15·0	>15·0
Wear areas (sq.inches)	<4·0	>4·0 ≤9·0	>9·0 ≤16·0	>16·0 ≤25·0	>25·0 ≤36·0	>36·0
	Points Scored					
Holes	5	9	11	13	14	15
Tears in wear area* ...	5	9	11	13	14	15
Frays	0·5	1	2	3	4	5
Wear areas	4	6	9	11	13	15

*For purposes of evaluating the serviceability of fabrics as such, instances of accidental tear, stitching failures, bar tacking failures and button failures are recorded, but not scored. After recording they are repaired.

Test results. In both the Phase I and the Phase II tests, distinct differences in wear among the experimental fabric types became evident. Within each test phase, it was possible to segregate the fabrics into four or five groups with statistically significant differences in wear. These are noted below.

Phase I

1. The 70/30 wool/polyester F_1 was the most durable of all the fabrics.
2. The 85/15 wool/polyester G_1 was the second most durable fabric.
3. The 70/30 wool viscose twill D_1 was the third most durable fabric.
4. There were no differences in durability between the 100 percent OD wool control A_1, the 100 percent 60's wool B_1, and the 100 percent 56's wool C_1 fabrics.
5. The 70/30 wool/viscose satin E_1 was the least durable of the seven fabrics.

Phase II

1. The 70/30 wool/nylon A_2 and the 70/30 wool/modacrylic E_2 were the most durable of all the fabrics.

2. The 85/15 wool/modacrylic F_2 and the 70/20/10 wool/viscose/nylon G_2 were the most durable of the remaining fabrics.

3. The 70/30 56's wool/3-den viscose C_2 and the 70/30 56's wool/5.5-den viscose D_2 were the next most durable fabrics.

4. The 85/15 wool/viscose B_2 and the 100 percent OD wool control S_2 were the least durable fabrics.

The wear scores observed in the two tests are given in Appendix B. Plots of the wear scores showing the trend in wear are given in Figures 6 (Phase I) and 7 (Phase II). It is of interest to compare these two sets of data.

In the Phase I test, after an initial period of very little wear, there was a gradual increase in the wear score and this increase appears to be roughly linear with the number of traversals on the course. In the Phase II test, the steep slope after the initial induction period tended to level off and become constant for most of the fabrics. No leveling was indicated even up to the 30th traversal (see Appendix B) for the fabrics of Phase I. There must have been some differences in the wear systems of the two phases to account for these observations.

In Phase II the observed differences among the fabric types became so pronounced as the test progressed that the four types having the highest wear scores (see Figure 7) were withdrawn from the test after the 20th traversal. Accordingly, comparisons of the relative wear of the different fabric types are made only up to and including the 20th traversal.

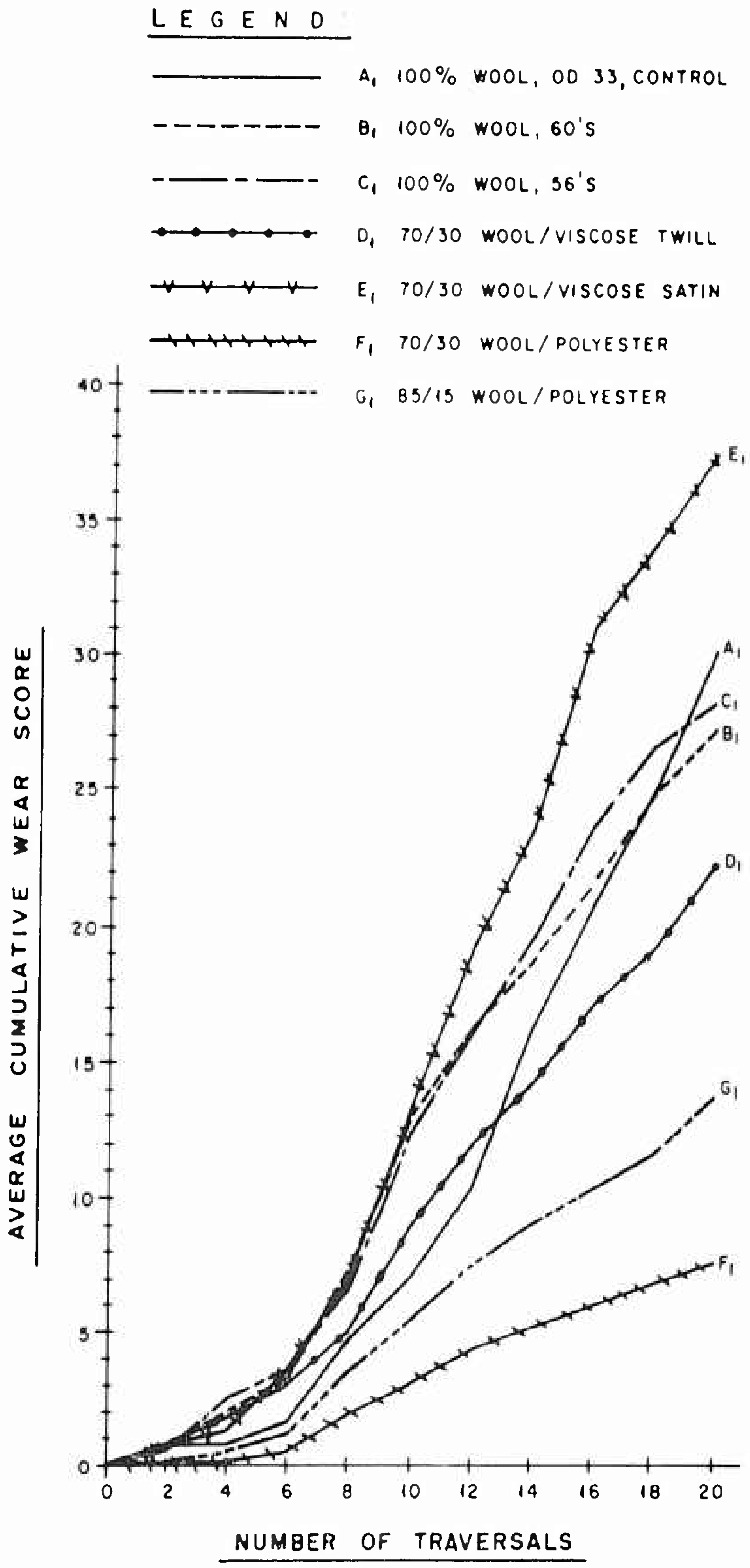


Figure 6. Average Cumulative Wear Scores (unadjusted) By Traversals - Phase I Test

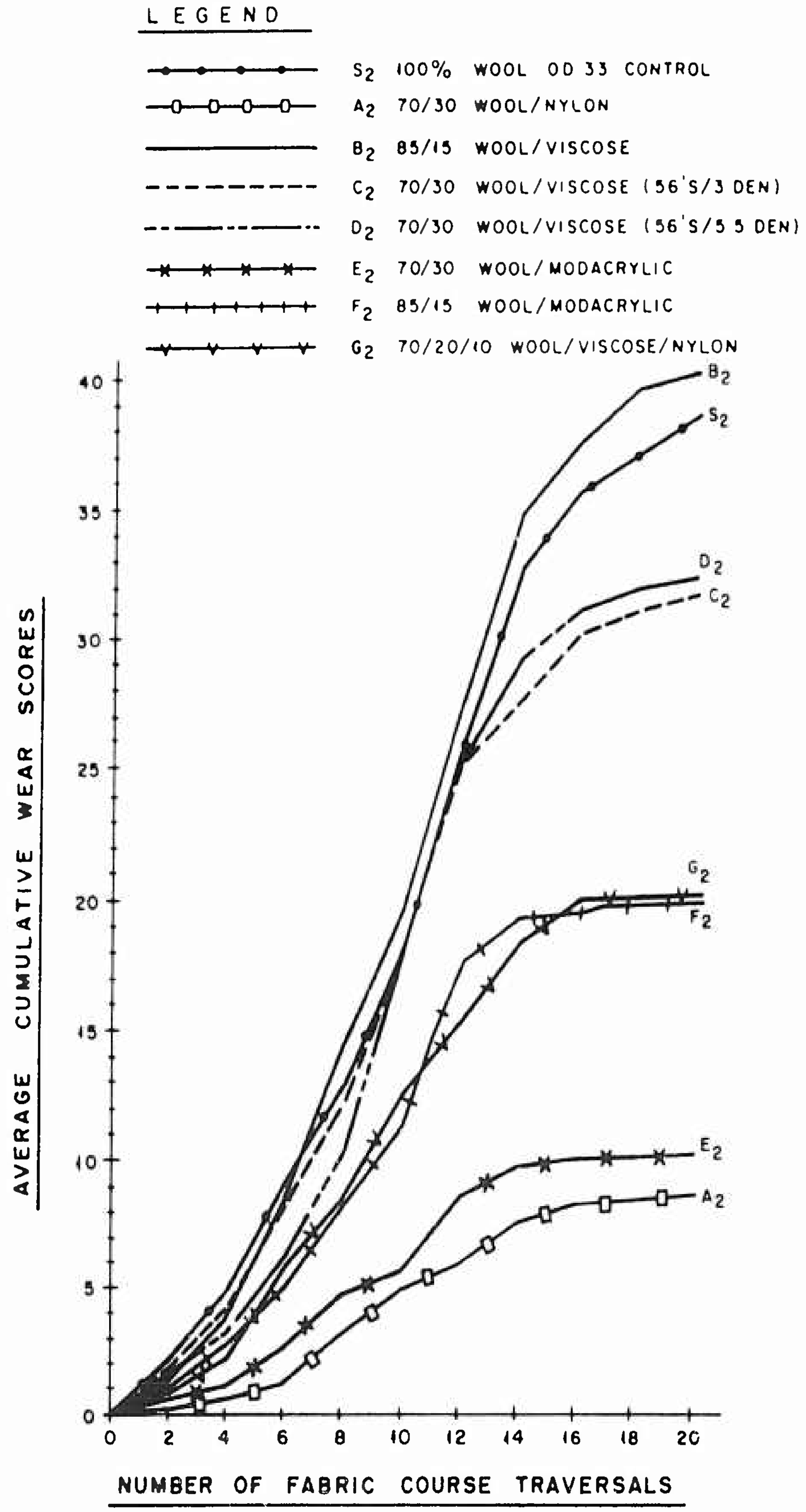


Figure 7. Average Cumulative Wear Scores by Traversals - Phase II Test

The only basis for equating the data from the two phases of the test was by means of the 100 percent wool OD 33 Control, which was used in both phases. The fact that the wear score of this fabric, after 20 traversals, was 30.1 in Phase I and 38.4 in Phase II indicates fairly good agreement for testing of this type, particularly since different test subjects were involved and a period of almost three years had elapsed between Phase I and Phase II. In order to compare the two sets of data, the wear score for each of the fabrics in the Phase I test was multiplied by the fraction $\frac{38.4}{30.1}$ (or 1.28), which is the ratio of the Phase II 20th traversal score of the control to its corresponding score in the Phase I test. A comparison of the wear scores, normalized or adjusted in this fashion, is given in Table VI.

TABLE VI

Wear Scores for Phase I (adjusted)* and Phase II Tests

QM R&E Code	Fort Lee Code	Fabric**	Phase I	Phase II	Correl. Factor	Wear Score***
G6007	A_2	70/30 wool/nylon	----	8.5	1.00	8.5
G6001	F_1	70/30 wool/polyester	7.6	----	1.28	9.8
G6003	E_2	70/30 wool/modacrylic	----	10.1	1.00	10.1
G6000	G_1	85/15 wool/polyester	13.8	----	1.28	17.7
G6002	F_2	85/15 wool/modacrylic	----	20.2	1.00	20.2
G5990	G_2	70/20/10 wool/visc/nylon	----	20.3	1.00	20.3
G5989	D_1	70/30 wool/viscose	22.4	----	1.28	28.7
G5998	C_2	70/30 56's wool/3d viscose	----	31.7	1.00	31.7
G5999	D_2	70/30 wool/5.5d viscose	----	32.2	1.00	32.2
G5992	B_1	100% wool (orig. control)	27.3	----	1.28	34.9
G5997	C_1	100% 56's wool	28.3	----	1.28	36.2
OD 33	A_1	100% wool OD 33 control	30.1	38.4	1.28 & 1.00	38.5
G6004	B_2	85/15 wool/viscose	----	40.2	1.00	40.2
G5996	E_1	70/30 wool/viscose, satin	37.6	----	1.28	48.2

---

* Adjustment factor, 1.28.

** Unless otherwise indicated, all fabrics were made with 60's wool in a 2x2 twill weave, and all non-wool yarns were 3-denier.

*** The <u>lower</u> the score, the <u>better</u> the wear resistance.

An obvious pattern emerges from this normalization. The non-viscose blends show the highest level of wear resistance, with the nylon, polyester, and modacrylic blends leading. Among each of the blends varying in ratio to wool, those with a 30 percent non-wool content show more wear resistance than those with 15 percent.

The 70/30 wool/viscose blends in the twill weave fall into an intermediate group from the standpoint of wear resistance. Apparently the denier of the viscose and the grade of wool do not have a significant influence on wear.

The three 100 percent wool fabrics show somewhat less resistance to wear than the 70/30 wool/viscose blends. The fabrics lowest in wear resistance are the 85/15 wool/viscose and the 70/30 wool/viscose in the satin weave.

In general, this ranking of the fabrics was not wholly unexpected. The superior wear resistance of nylon had been recognized. Experience with polyesters had indicated that their wear resistance is fairly close to that of nylon. While information on the relative wear of the modacrylics has not been available in the literature, laboratory data have indicated that the wear resistance of this type of fiber would be rather low, whereas these data rank the modacrylics rather close to the polyester blends.

The ranking of the wool/viscose twills as compared to the all-wools indicates that there may be a minimum point in their blend composition-wear curves somewhere between 0 and 30 percent of viscose. A plot of blend composition versus wear score for the fiber combinations tested is shown in Figure 8.

b. Laboratory Abrasion Tests

The seven blended fabrics tested on the Fort Lee Fabric Course during Phase II were also tested at the Quartermaster Research and Engineering Command in Natick, Massachusetts. Two test instruments were used: the flex element of the Stoll Flex Abrader, Model CS-39, using Blade 396; and a new Sand Abrader that was designed in the Quartermaster laboratories specifically to simulate the type of wear encountered on the fabric course.

The Stoll test, using warp direction abrasion only, was conducted on the fabrics to the point of rupture. The fabrics were evaluated both in their original condition and after chloroform extraction to eliminate the influence of lubricants. During this test, 4 pounds of tension was applied to the fabric at the yoke holding the blade, and 1 pound of pressure was applied perpendicular to the fabric surface.

In addition, these same seven Phase II blends were sand-abraded to give what Rabinowicz has described as "3-body wear" in which "a loose abrading medium such as sand is rubbed between two bodies producing wear in both or in one" (<u>15</u>). The term "3-body wear" is probably correctly applied to the type of wear action occurring at the Fort Lee wear course where grains of sand are picked up by the fabric and carried to subsequent obstacles, with a resulting interaction between sand, fabric, and the wood, stone, or concrete of the obstacles. In order to reproduce this phenomenon in the laboratory, an abrader was designed (the general plan is shown in Figs. 9 and 10) with cement-floored troughs into which sand can be fed at a relatively constant rate. Fabric samples are mounted on weighted moving arms which force the fabric back and forth through the bed of sand and along the brick until a hole appears. The versatility of this instrument

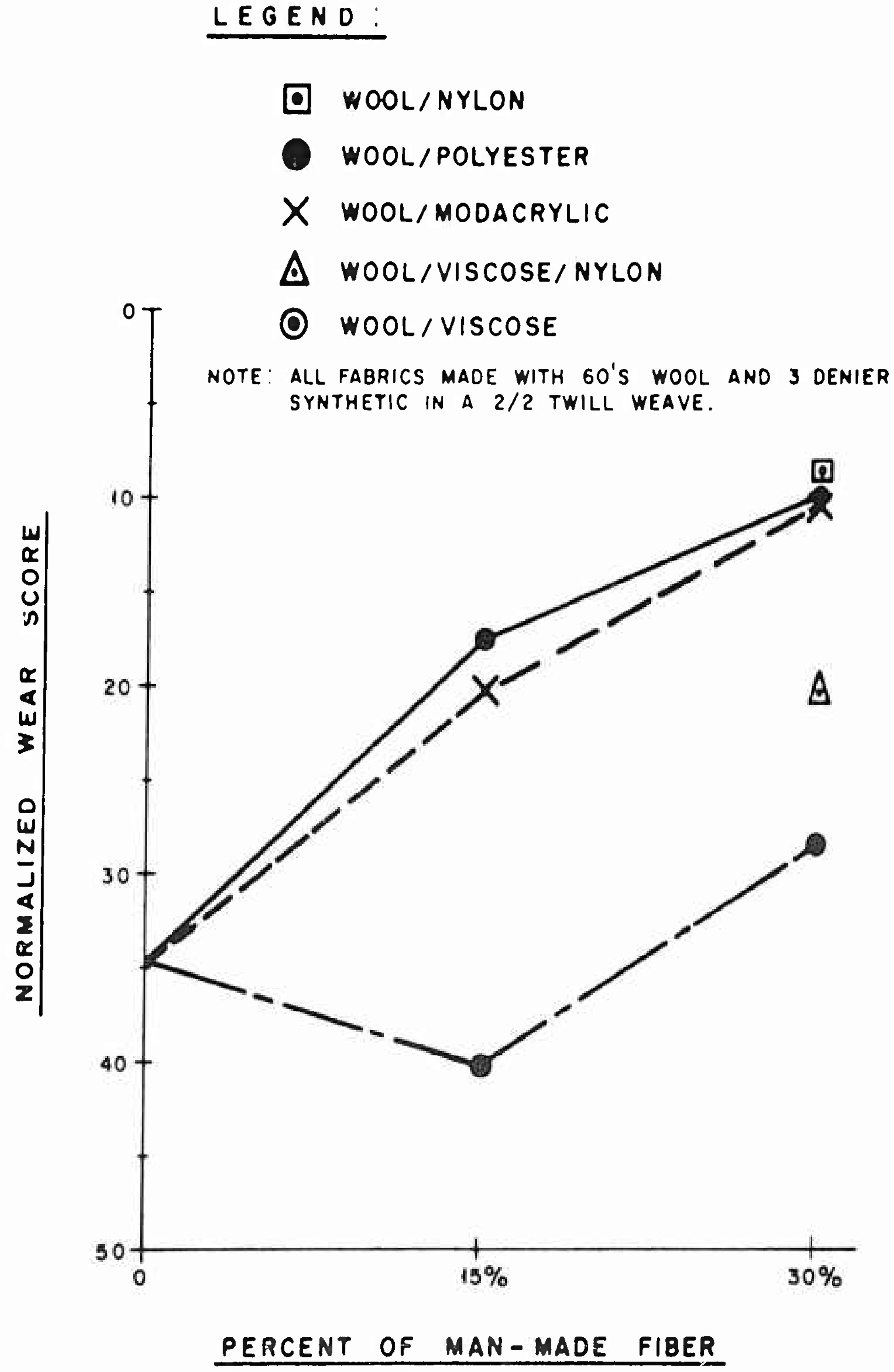


Figure 8. Effect of Man-Made Fiber Content on Wear - Phase I and Phase II Tests

and its high degree of correspondence with the abrasive action on the Fort Lee fabric course had previously been demonstrated.

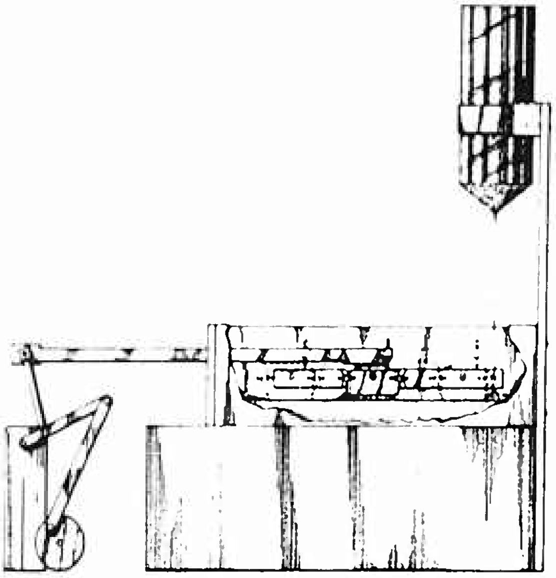


Figure 9. Sand Abrader - Side View

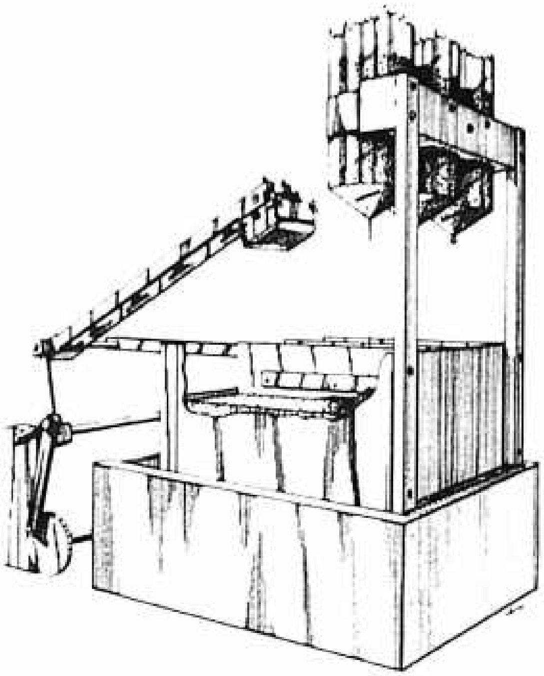


Figure 10. Sand Abrader - Showing Under Surface of Arm

The results of these tests, and also of the earlier Stoll test carried out on the original fabrics of this study (2) in their unextracted or original state to the point of threadbareness, are given in Table VII. The fabrics are listed in the order of their decreasing wear resistance as indicated by their fabric course or field wear scores (with the Phase I scores adjusted by the correlating factor of 1.28).

TABLE VII

Results of Field Wear and Laboratory Warp-Direction Abrasion Tests

Fabric	Field Wear* (score)	Stoll Flex Abrasion: To Threadbare, Orig. Cond. (score)	Stoll Flex Abrasion: To Rupture, Orig. Cond. (score)	Stoll Flex Abrasion: To Rupture, Extracted (score)	Sand Abrasion Orig. Cond. (rank)
70/30 W/N	8.5	2870	18670	8890	1
70/30 W/P	9.8	3260	--	--	--
70/30 W/M	10.1	1180	1520	1310	3
85/15 W/P	17.7	4340	--	--	--
85/15 W/M	20.2	1020	2200	1000	4
70/20/10 W/V/N	20.3	2030	5210	2320	2
70/30 W/V	28.7	1090	--	--	--
70/30 W/V 56's/3d	31.7	1330	2910	1670	5
70/30 W/V 56's/5.5d	32.2	1500	3217	1280	6
100 W	34.9	960	--	--	--
100 W 56's	36.2	1110	--	--	--
100 W OD 33 control	38.5	--	--	--	--
85/15 W/V	40.2	2110	3000	1300	7
70/30 W/V satin	48.2	1220	--	--	--
85/15 W/N		2130			
70/30 W/V gabardine		870			
70/30 W/V crowfoot		1040			
70/30 W/V Mayo twill		1200			
85/15 W/A-1		1200			
70/30 W/A-1		1190			
85/15 W/A-2		1360			
70/30 W/A-2		1590			

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* Scores of fabrics coded with a subscript of 1 (Phase I-tested) have been adjusted by a factor of 1.28.

Note: A ranking of 1 indicates the best wearing qualities.

4. Comparison between Field Wear and Laboratory Test Results

A comparison of the Stoll flex abrasion scores and the fabric course scores is shown in Table VIII.

TABLE VIII

Stoll Flex Abrasion and Wool Fabric Course Data - Phase II

Fabric	Stoll Flex Abrasion To Rupture (score)	(rank)	To Threadbare (score)	(rank)	Wool Fabric Course (score)	(rank)
A_2 70/30 wool/nylon	8890	1	2870	1	8.5	1
E_2 70/30 wool/modacrylic	1310	4	1180	6	10.1	2
F_2 85/15 wool/modacrylic	1000	7	1020	7	20.2	3
G_2 70/20/10 wool/visc/nylon	2320	2	2030	3	20.3	4
C_2 70/30 wool/visc (3d)	1670	3	1330	5	31.7	5
D_2 70/30 wool/visc (5.5d)	1280	6	1500	4	32.2	6
B_2 85/15 wool/visc	1300	5	2110	2	40.2	7

Note: No. 1 represents the best ranking fabric.

Correlation between the abrasion-to-rupture and fabric-course rankings is not significant. Correlation between the abrasion-to-threadbareness and field wear is even poorer. It has been observed that, in general, laboratory abrasion instruments tend to rank fabrics containing nylon higher and fabrics containing modacrylic fibers lower than does the wear course. Perhaps this is because, in the Stoll tester, there is an interaction between the relatively low-softening-point modacrylic fibers and the metal of the blade and this leads to the generation of an appreciable amount of heat which alters the stress-strain characteristics and accordingly the inherent wear properties of thermoplastic fibers. The degree to which this interaction occurs will vary among the various abrasion instruments and is a function of the nature of the contacting surfaces, the duration of the contact, and the conductivity of the solids.

It is conceivable that alteration of the Stoll testing procedure to compensate for the sensitivity of fabrics to elevated temperatures and lubrication might somewhat improve the observed relationships. Also, it is possible that Stoll flex abrasion is more characteristic of the "adhesive" type of wear described above, and that wear course abrasion is related more to "abrasive" wear. Furthermore, we must keep in mind that the wear course itself is not the ultimate criterion of use. It would be desirable to investigate the correlation between the accelerated wear resulting from traversals of the wear course and wear under actual field operations.

On the other hand, a comparison of the sand abrader rankings made by three observers and the fabric course results shows an excellent correlation.

Four of the averaged sand abrader rankings are identical with those of the fabric course, two differ by only one point, and one differs by only two points (Table IX). The sand abrader places the wool/viscose/nylon blend G_2 ahead of the two wool/modacrylic blends E_2 and F_2, and again this is a manifestation of the tendency of laboratory instruments to rank nylon-containing fabrics higher and modacrylic fabrics lower than the wear course.

TABLE IX

Sand Abrasion Evaluation and Wool Fabric Course Data - Phase II

Fabric	Wool Fabric Course Rankings	Sand Abrader Rankings*				Avg. Ranking
		Obs.A	Obs.B	Obs.C	Avg.	
A_2 70/30 wool/nylon	1	1	1	1	1.0	1
E_2 70/30 wool/modacrylic	2	3	3	4	3.3	3
F_2 85/15 wool/modacrylic	3	4	5	3	4.0	4
G_2 70/20/10 wool/visc/nylon	4	2	2	2	2.0	2
C_2 70/30 wool/visc (3d)	5	5	4	5	4.7	5
D_2 70/30 wool/visc (5.5d)	6	6	6	6	6.0	6
B_2 85/15 wool/visc	7	7	7	7	7.0	7

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*By 3 observers, A, B, C.

5. Comparison between Field Wear and the Mechanical Properties of Fibers

In evaluating factors contributing to the observed field performance of the blended serges, an attempt was made to apply, in modified form, the technique recommended by Hamburger (7) for predicting the abrasion resistance of a fabric in terms of the inherent energy-absorbing characteristics of the component fibers or yarns. Two systems were used to make these comparisons. In one, the wear scores of the fabrics were plotted against one-half the product of the strength-to-rupture and the elongation-to-rupture values for the yarns if the stress-strain curve is assumed to be linear. In the other system, the wear scores of the fabrics were plotted against a factor derived by weighting the work-to-rupture values of the component fibers, as reported in the literature, by their percentage composition in the blend. The latter system has the disadvantage of not being comparable for the various fiber types because of the different physical forms in which they have been evaluated.

Figure 11 represents the wear scores plotted against the work coefficients computed directly from the yarn strength and elongation data, while Figure 12 represents the wear scores plotted from weighted fiber data. The agreement is quite good in Figure 11. Figure 12 shows a definite trend. In both charts, the leveling-off tendency at the high work-to-rupture values probably indicates that there is an upper limit to the

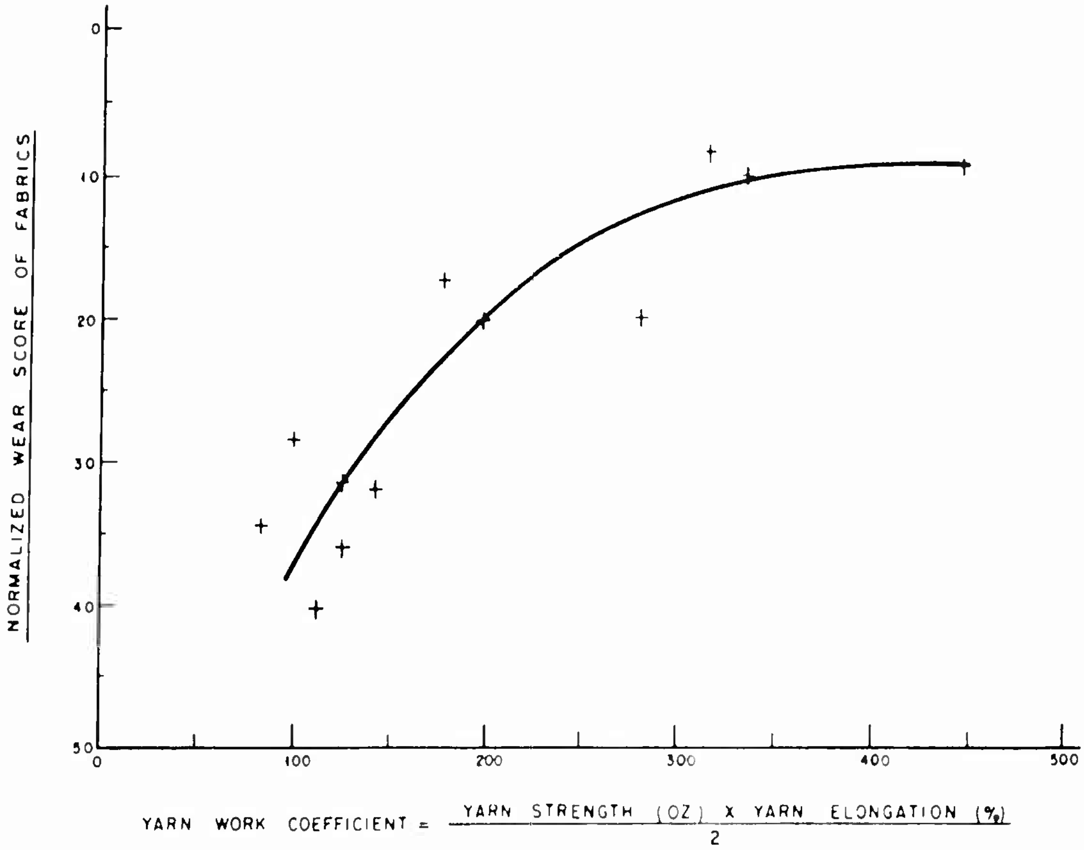

Figure 11 - Relationship between Fabric Wear Course Scores and Yarn Work Coefficients

contribution that can be made by the mechanical properties of the component fibers to ultimate wear resistance and that, at high work-to-rupture levels, geometric factors begin to play a more significant role. In general, the data of this study substantiate the generally accepted belief that the mechanical properties of fibers do significantly influence wear resistance and that it is possible to select fiber types in the design of a fabric that will provide enhanced wear for specific applications.

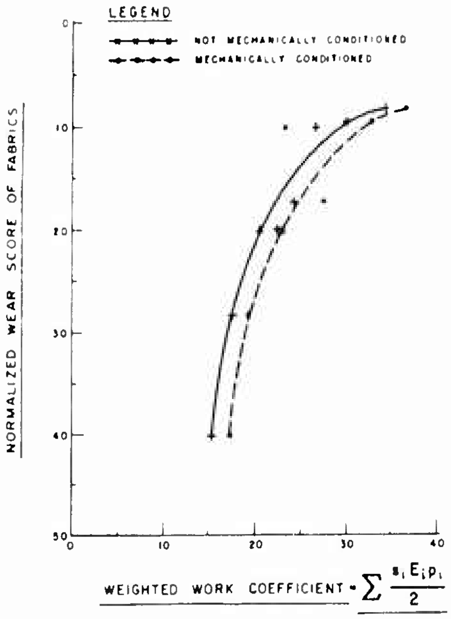

Figure 12 - Relationship between Fabric Wear Course Scores and Weighted Work Coefficients

6. Conclusions

As pointed out in the introduction, one cannot safely generalize about the behavior of fabrics from data obtained on samples made by a single manufacturer under a very specific set of conditions for, obviously, the performance of a fabric may be improved with experimentation and with further production experience. However, the wear test results obtained in this study appear to be sufficiently plausible from the standpoint of practical expectations and consistency with theory to lead to some general conclusions. Accordingly, within the limits of experimental error and assuming that there is a real significance to the wear course at Fort Lee in terms of what might be expected in actual combat wear, the following is tentatively stated:

a. From the standpoint of wear, blends of wool with nylon, polyester, or modacrylic fibers are superior to all-wool or to blends of wool with viscose.

b. Among the hydrophobic fibers, 30 percent blends with wool provide a higher level of wear resistance than 15 percent blends.

c. The effect of weave in the specific samples tested was not pronounced.

d. Wear resistance of a fabric is in general, a function of the energy-absorbing properties of its component fibers. Those fibers providing the highest integrated work values produced the best wear-scoring fabrics.

e. The sand abrader provides a type of action in the laboratory that agrees quite well with that provided by the wool wear course.

f. The Stoll Flex Abrader does not give results that agree closely with those observed on the wear course, probably because of its sensitivity to thermal and lubricating effects.

g. The conclusions on durability reached in Textile Series Report 107 (2) have generally been borne out by subsequent studies, except that the modacrylic blends were found to be far superior to the all-wool.

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APPENDIX A LABORATORY DATA ON PRODUCTION

Property	All Wool	[illegible] Wool/Vis	Wool/Vis/Nyl	[illegible] Wool/Ny[illegible]	Gabardine	Crowfoot	Mayo Twill	Satin	[illegible] Wool
Weight (oz/sq yd)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.1	[illegible]
Texture [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wool content (%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] (%)	[illegible]	--	[illegible]	[illegible]	[illegible]	--	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.1	[illegible]
Air permeability [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible], WxF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	--	[illegible]
[illegible] stiffness, [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] stiffness, [illegible], WxF	--	[illegible]	--	--	--	--	--	--	--
[illegible] stiffness, [illegible], WxF	[illegible]	[illegible]	[illegible]	[illegible]	--	--	--	--	--
[illegible] stiffness, [illegible], WxF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] stiffness, [illegible], WxF	--	[illegible]	--	--	--	--	--	--	--
[illegible] stiffness, [illegible], WxF	[illegible]	[illegible]	[illegible]	[illegible]	--	--	--	--	--
Crease [illegible], WxF (%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Crease retention (%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				[illegible]		[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tensile strength, WxF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tear strength, WxF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible], WxF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1221x1540	1110x1230
Shrinkage, [illegible], WxF (%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.4x0.0
Shrinkage, [illegible] laundry, WxF (%)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.8x-0.1
Ignition time [illegible]	a	[illegible]	a	a	[illegible]	[illegible]	[illegible]	18.1	a
Flame [illegible]				[illegible]	[illegible]	3.3	[illegible]	8.3	0
Flame rate [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	0
Afterflame, WxF sec	11x4	[illegible]	[illegible]	26x11	[illegible]	[illegible]	15x13	[illegible]	15x24
Afterglow, WxF sec	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	0	0
Char length, WxF cm	4x3	4x5	4x4	[illegible]	4x5	4x6	4x5	5x4	4x5
Seam strength (lb)	110	106	128	154	111	105	100	105	110
Seam efficiency (%)	94	95	95	92	99	88	93	95	95
Skip stitches/20 yd	--	--	44	110	—	—	—	—	--
Needle replacements/20 yd	—	—	0	0	--	—	--	--	--

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* From QM R&E Textile Series Rept. 107, Natick, Mass., 1959

a) Samples did not ignite in 60 seconds;

b) Three out of five samples did not ignite in 60 seconds;

c) Two out of five samples did not ignite in 60 seconds;

d) Fabric melted and continued to flame in droplets;

e) Value for one sample; two samples burned to the end;

f) Average for two samples; one sample burned to the end;

g) Samples melted and flamed to the end;

h) Samples flamed to the end;

i) Fabric broke some distance from the seam;

j) No count was made, because high-speed sewing could not be maintained.

OF 15-[illegible] SERGE FABRICS*

[illegible] [illegible] Sea Wool [illegible] Vis	[illegible] 70% Sea Wool 30% Sgd Vis	[illegible] 70% Wool 30% Nylon	[illegible] 85% Wool 15% Polyest	66001 70% Wool 30% Polyest	66004 85% Wool 15% Vis	66002 85% Wool 15% Modacr	66003 70% Wool 30% Modacr	66005 85% Wool 15% Acryl-1	66006 70% Wool 30% Acryl-1	66008 85% Wool 15% Acryl-2	66009 70% Wool 30% Acryl-2
[illegible]	18.5	[illegible]	[illegible]	19.2	15.6	18.8	17.6	17.6	18.0	19.2	18.9
[illegible]	[illegible]	66x55	69x55	70x52	70x52	70x55	69x55	69x54	70x52	70x55	70x50
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	83.0	73.1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52	56
[illegible]	29	29	[illegible]	[illegible]	[illegible]	32	[illegible]	[illegible]	26	28	27
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	42	46	48
17.2	17.7	[illegible]	16.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.3	19.8	18.1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.1	6.9
[illegible]	1.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18	18
--	[illegible]	16x19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10x21	[illegible]	[illegible]	14x55
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.93x0.91	[illegible]	[illegible]	0.95x0.81
[illegible]	[illegible]	[illegible]	—	--	--	--	[illegible]	--	[illegible]	--	1.21x1.03
—	—	[illegible]	—	[illegible]	--	[illegible]	[illegible]	—	[illegible]	—	1.07x.98
[illegible]	[illegible]	[illegible]	5.1x1.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.1x3.1
[illegible]	[illegible]	[illegible]	—	--	—	--	[illegible]	—	7.8x5.3	--	11.2x7.0
—	--	[illegible]	--	[illegible]	--	[illegible]	[illegible]	—	6.3x4.5	--	8.5x6.0
72x79	[illegible]	79x81	[illegible]	[illegible]	82x82	[illegible]	[illegible]	[illegible]	[illegible]	83x82	79x81
[illegible]	[illegible]	[illegible]	82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0
Mod.	Mod.	Low	Low	Low	Mod.	High	High	High	High	High	High
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	177x131	190x145
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.2x5.3
[illegible]	[illegible]	2870x3240	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1360x1880	1590x1910
2.7x0.7	5.0x0.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.4x0.9	3.2x0.8
[illegible]	5.3x1.0	[illegible]	5.8x1.9	[illegible]	[illegible]	5.5x2.0	[illegible]	4.6x0.9	3.7x0.8	5.1x1.8	5.3x1.2
[illegible]	14.6	*	[illegible]	[illegible]	21.2	22.1	17.5	*	*	*	*
[illegible]	15.1	0	5.3	[illegible]	15.0	2.4	[illegible]	0	0	0	0
[illegible]	0.03	0	[illegible]	0.05	0.01	0.04	0.05	0	0	0	0
[illegible]	15x22	46x51	[illegible]	44x43	10x23	5x9	41x9	40x40	50x72	16x9	23x29
0	0	0	0	0	0	0	0	0	0	0	0
4x4	4x6	8	8	8	[illegible]	4x3	[illegible]	[illegible]	8	5x4	[illegible]
1101	1101	188	1581	1166	105	141	133	115	114	112	140
103	99	93	101	94	96	99	84	95	86	89	97
—	--	115	150	3	—	20	115	18	4	5	44
—	--	0	4L 2R	3L 2R	—	0	0	0	0	0	0

Appendix B

AVERAGE CUMULATIVE WEAR SCORES BY TRAVERSALS OF WOOL FABRIC COURSE

		2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
(Controls)	A_1	0.69	0.83	1.67	4.72	7.14	12.31	15.19	20.78	25.00	30.11 38.54*	34.92	38.42	43.47	49.89	57.42
	S_2	2.21	4.70	8.82	12.79	18.06	25.65	32.35	35.38	36.85	38.38	**	**	**	**	**
(Correlating Factor)		3.20	5.66	5.28	2.71	2.53	2.08	2.13	1.70	1.47	1.28					
	B_1	0.83	2.06	3.28	7.42	13.11	16.42	17.89	21.78	24.89	27.31 34.95*	32.17	36.91	39.97	45.94	52.39
	C_1	0.81	2.47	3.58	6.64	12.53	16.36	19.50	23.86	26.64	28.28 36.19*	32.50	36.47	37.72	43.89	52.22
	D_1	0.83	1.81	3.19	5.14	9.11	12.06	14.25	17.14	19.14	22.44 28.72*	24.81	29.44	34.28	39.56	43.61
	E_1	0.69	1.25	3.56	7.22	13.58	19.25	23.64	31.17	34.22	37.64 48.19*	43.53	47.25	56.17	62.50	71.92
	F_1	0.00	0.14	0.56	1.94	3.06	4.31	5.14	5.97	6.81	7.64 9.78*	9.27	9.67	11.05	12.97	15.17
	G_1	0.00	0.42	1.11	3.47	5.42	7.50	9.03	10.25	11.64	13.83 17.70*	15.33	17.64	20.33	22.83	29.19
	A_2	0.29	0.74	1.32	3.24	4.85	6.32	7.50	8.23	8.38	8.53	8.53	8.53	8.53	8.79	9.09
	B_2	1.32	3.52	8.21	11.24	19.35	27.00	34.62	37.38	38.50	40.18	**	**	**	**	**
	C_2	1.91	4.12	8.09	12.35	18.06	24.97	27.68	30.06	31.03	31.73	**	**	**	**	**
	D_2	1.62	3.82	6.74	13.50	18.32	25.15	29.18	31.03	31.82	32.31	**	**	**	**	**
	E_2	0.74	1.32	2.50	4.71	6.14	8.50	9.68	9.85	10.00	10.12	10.12	10.12	10.24	10.50	11.03
	F_2	1.18	2.65	5.00	8.09	11.26	17.50	19.38	19.53	20.12	20.23	20.38	20.38	20.38	20.50	20.79
	G_2	1.02	2.35	5.74	8.24	12.32	15.08	18.29	19.71	19.97	20.26	20.38	20.38	20.71	20.71	20.76

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*Adjusted by correlating factor of 1.28
**Withdrawn after 20th traversal.

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